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STRUCTURAL OPTIMIZATION OF LNG CARRIER

Summary

The purpose of the paper is to present main results of LNG carrier structural optimization. The work has been carried through EU FP6 project IMPROVE. Coarse mesh FE model has been developed in extent of the three cargo holds using MAESTRO software. The strength calculation has been carried out according Bureau Veritas (BV) Rules. The objective of the whole optimization process was to distribute the material more effectively in order to reduce weight/cost and to improve the structural safety. Sensitivity analysis has been performed in order to investigate the influence of a web frame spacing, longitudinal stiffener spacing and material type on the defined design objectives. Structural optimization of LNG structure, for one cargo hold, resulted in mass decrease of about 424 t, or 10.8%, cost of the structure was decreased for about 5%, structural safety was increased and VCG was slightly decreased for about 20 cm compared to prototype structure.

Key words: Ship structural optimization, LNG carrier, FEM

STRUKTURNA OPTIMIZACIJA BRODA ZA PRIJEVOZ UKAPLJENOG PRIRODNOG PLINA

Sažetak

Cilj rada je prikazati glavne rezultate strukturne optimizacije broda za prijevoz ukapljenog plina koja je provedena u okviru EU FP6 istraživačkog projekta IMPROVE. Izgrađen je grubi model konačnih elemenata koji obuhvaća tri teretna prostora korištenjem programskog paketa MAESTRO. Proračun čvrstoće proveden je prema Pravilima Bureau Veritas (BV). Cilj cjelokupnog optimizacijskog postupka bio je optimalna redistribucija materijala s ciljem smanjenja težine/cijene i poboljšanja sigurnosti. Provedena je studija senzitivnosti s ciljem istraživanja utjecaja razmaka okvirnih rebara, razmaka uzdužnjaka i tipa materijala na definirane projektne ciljeve. Strukturna optimizacija, na razini jednog skladišta, rezultirala je u smanjenju mase oko 424 t (10.8%), cijena je smanjenja za oko 5%, sigurnost je povećana, dok je VCG je blago smanjen za oko 20cm, u usporedbi s prototipnom konstrukcijom.

Ključne riječi: strukturna optimizacija, brod za prijevoz ukapljenog prirodnog plina, MKE

1. Introduction

The very effective and practical way to transport gas between continents is by ships, in liquid form. The gas is liquefied by subjecting it to pressure and/or low temperature. Liquid Natural Gas (LNG) carriers are special ships built to transport large volume of LNG at its atmospheric pressure boiling point of $-163\text{ }^{\circ}\text{C}$. The capacity of these ships is now typically between $100\,000\div 220\,000\text{ m}^3$. The LNG ships with membrane type are mostly built in recent years. Membrane tanks are non-self-supporting tanks, which consist of thin layer (membrane) supported through insulation to the adjacent hull structure [1].

The work presented through this paper has been done as a part of EU FP6 project IMPROVE. The objective of University of Zagreb, task 6.2 in WP6, was to develop, analyze and optimize a global 3D FEM model of LNG ship ("free ballast" design) in an integrated multiple criteria decision making environment by using the advanced analysis techniques (FEM, ultimate strength of panel and hull girder) coupled with methods of design synthesis (sequential fractional factorial experiments, genetic algorithm, robustness measure, etc.) at the earliest stage of the design process, which innovatively considers structure, production, operational aspects, performance, and safety criteria on a concurrent basis in order to achieve improved and competitive structural design [2].

2. Global 3D FEM optimization with OCTOPUS/MAESTRO

Generally, structural design may be divided into concept, preliminary and detail design. Concept design is defined as the phase in structural design when geometry and topology are open to modification and structural variants are analyzed in accordance with the needs of the problem multiple stakeholders (head designer, owner, etc). Benefits of optimization procedure in this phase are the biggest.

The design environment of MAESTRO software [3, 4], capable of imbedding multiple quality criteria for structural design, is used to provide the decision support problem (DSP) rationale for multi-criteria (weight, cost and centre of gravity) based optimization [5].

The general mathematical model contains the analysis and the synthesis modules. They have been developed and implemented in the decision support systems MAESTRO and OCTOPUS [6]. They can be decomposed, in principle, into six meta-systems of which two basic ones provide physical and environmental definitions of the problem / process and other four are behavioral systems for modeling response, adequacy, reliability and quality, as described in [7] and are invoked into the design problem definition modules and coupled with different optimization solvers (Σ) into multi-attribute multi-level synthesis procedure [7, 8].

3. Design procedure

The general procedure developed for design includes the formulation of design support problem (DSP), i.e. identification of variables, attributes, constraints, formulation of analytical model (response and feasibility modules), selection of synthesis model and final selection of the solution strategy for the manipulated problem. The analysis of prototype structure \mathbf{P}^0 enables fair comparisons with other concepts, denoted \mathbf{P}^j . The optimal solution \mathbf{P}^j , also denoted as \mathbf{O}^j , is standardized at the end of the procedure (denoted as \mathbf{D}^k). The overall description of the design procedure, divided into design phases, is given in Fig. 1.

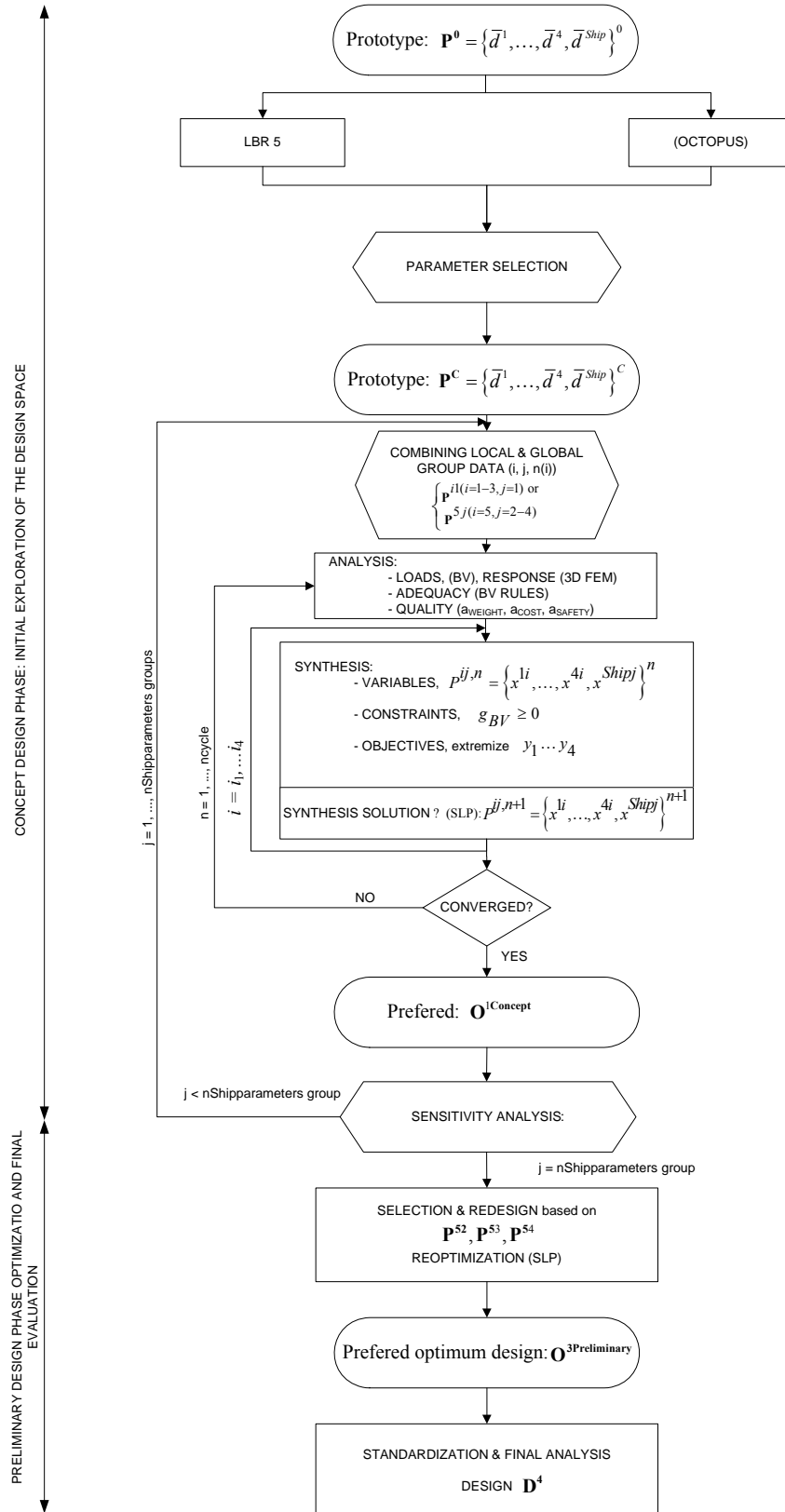


Fig. 1 Design procedure

Slika 1. Projektni postupak

3.1. Design problem identification

The design variables: $\mathbf{x}^{Total} \subseteq \mathbf{P}^J = \{ \mathbf{x}^{Ship-j}, \{ \mathbf{x}^{Subset-i} \} \}$, where n-tuple \mathbf{x}^{Total} includes all design variables in the area under consideration, can be decomposed into subsets of

substructure (local) variables \mathbf{x}^i and each of those subsets can be further decomposed into elements of sets related to topology $\mathbf{x}^{(T)}$, geometry $\mathbf{x}^{(G)}$, scantlings $\mathbf{x}^{(S)}$ and material $\mathbf{x}^{(M)}$. A set of global variables is denoted as $\mathbf{x}^{\text{Ship-j}}$. Materials used at present are mild steel and high tension steel. Scantling variables are associated to a specific strake. Also, strakes are sorted according to a structural area: plate, stiffeners, frames and longitudinal girders. Fig. 2 represents 3-Hold FE structural model with two basic sub models (tank and cofferdam structures) that were jointly optimized. Tank structure is composed of longitudinal strakes (rows of stiffened panels, and longitudinal girders, as well as transverse structure consisting of strakes running transversely (floors, deck beams), vertically (side webs) and slanted (bilge and topside structure).

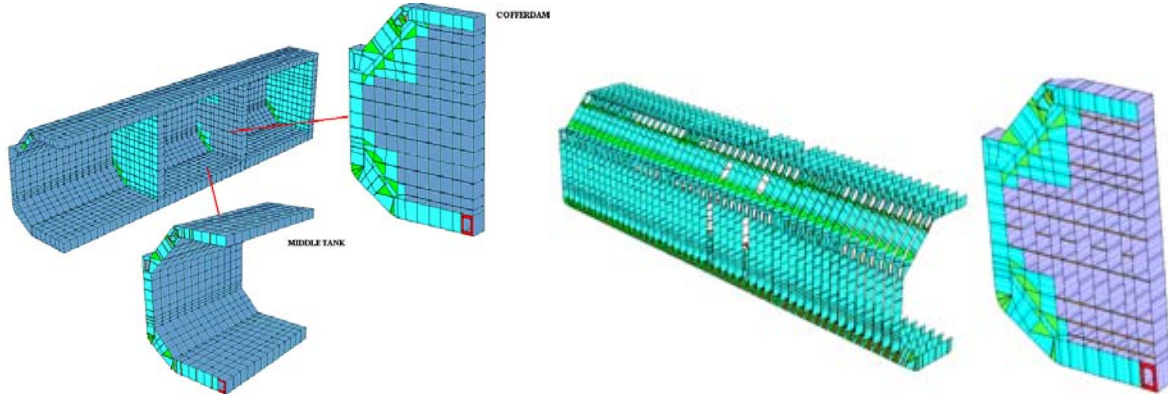


Fig. 2 Structural model and optimization sub modules with cofferdam inner structure

Slika 2. Strukturni model i optimizacijski pod-modeli sa unutarnjom strukturom koferdama

Design variables defined for the middle tank structure are given in Table 1. Cofferdam structure includes strakes in the stiffened shell plating, horizontal stringers and vertical webs. Design variables defined for the structure are given in Table 1.

Table 1. Design variables definition in tank and cofferdam for scantling optimization and sensitivity studies

Tablica 1. Definicija projektnih varijabli za optimizaciju i analizu senzitivnosti strukture tanka i koferdama

		Sets of variables		Subsets	Elements of sets	Range of sets
		Set	Description			
Scantlings	TG	$\mathbf{x}^{\text{ShipJ}}$	General		s_w , bbs, MS	
	Tank	\mathbf{x}^{1S}	Plating & stiffeners	\mathbf{x}_m^{1S}	t_{plat} , n_{stiff} , h_{stiff} , t_{sweb} , b_{sflange} , t_{sflange}	$m = 1, 2, \dots, n_{\text{strakes}}$
			Longitudinal girders	$\mathbf{x}_{k1}^{\text{Girders}}$	t_{gweb}	$k1 = 1, 2, \dots, n_{\text{girders}}$
		\mathbf{x}^{2S}	Transverse frames	$\mathbf{x}_{k2}^{\text{Frames}}$	t_{fweb}	$k2 = 1, 2, \dots, n_{\text{frames}}$
	Cofferdam	\mathbf{x}^{3S}	Vertical stringers	\mathbf{x}_{k3}^3	t_{plat} , n_{stiff}	$k3 = 1, 2, \dots, n_{\text{vertstring}}$
		\mathbf{x}^{4S}	Horizontal stringers	\mathbf{x}_{k4}^4	t_{plat} , n_{stiff}	$k4 = 1, 2, \dots, n_{\text{horstring}}$
			Plating	\mathbf{x}_{k5}^4	t_{plat} , n_{stiff} , h_{stiff} , t_{sweb} , b_{sflange} , t_{sflange}	$k5 = 1, 2, \dots, n_{\text{strakes}}$
Sensitivity	Tank	$\mathbf{x}^{\text{Ship2}}$	Web spacing	$\mathbf{x}_{k6}^{\text{Frame spac.}}$	s_w	$k6 = 1, 2$
		$\mathbf{x}^{\text{Ship3}}$	Stiffener spacing	$\mathbf{x}_{k7}^{\text{Stiff. spac.}}$	bbs	$k7 = 1, 2, \dots, n_{\text{strakes}}$
		$\mathbf{x}^{\text{Ship4}}$	Material	$\mathbf{x}_{k8}^{\text{SM}}$	MS, HTS	$k8 = 1, 2, \dots, n_{\text{strakes}}$
	Cofferdam	$\mathbf{x}^{\text{Ship3}}$	Stiffener spacing	$\mathbf{x}_{k9}^{\text{Stiff. spac.}}$	bbs	$k9 = 1, 2, \dots, n_{\text{strakes}}$
		\mathbf{x}^{Ship}	Stiffener orientation			

The selected design attributes, expressed as function of design variables $\mathbf{x}^{\text{Total}}$, were $y_1 = \text{minimize } a_{\text{WEIGHT}}$, $y_2 = \text{minimize } a_{\text{COST}}$ and $y_3 = \text{maximize } a_{\text{SAFETY}}$. Measure of safety is defined via total number of unsatisfied constraints and relative adequacy index (*RAI*). It is calculated using histogram of the values of various constraints as ratio between the area under the distribution of positive values and total area consisting of area under positive and negative values of constraints. The design constraints and requirements are determined in several ways. Minimum and maximum values were specified by the shipyard. In addition to this, the requirements based on technology and experiences have to be declared in form of various ratios that combine frame, girder and stiffener scantlings. Linear constraints for equivalent HP profiles have to be declared in order to fit the standard HP profiles in the best possible way. Also, in order to satisfy necessary structural strength adequacy parameters had to be equal or greater than zero. MAESTRO nonlinear constraints are given in Table 2.

Table 2. MAESTRO structural adequacy constraints with safety factors

Tablica 2. MAESTRO - funkcije ograničenja na temelju podobnosti sa koeficijentima sigurnosti

Item	Limit state	Description	BV Safety factor, γ
1	PCSF	Panel Collapse - Stiffener Flexure	1.04
2	PCCB	Panel Collapse - Combined Buckling	1.04
3	PCMY	Panel Collapse - Membrane Yield	1.224
4	PCSB	Panel Collapse - Stiffener Buckling	1.04
5	PYTF	Panel Yield - Tension Flange	1.224
6	PYTP	Panel Yield - Tension Plate	1.224
7	PYCF	Panel Yield - Compression Flange	1.224
8	PYCP	Panel Yield - Compression Plate	1.224
9,10	PSPB	Panel Serviceability - Plate Bending	1.00
11	PFLB	Panel Failure - Local Buckling	0.90
12	GCT	Girder Collapse Tripping	1.04
13	GCCF	Girder Collapse Compression in Flange	1.04
14	GCCP	Girder Collapse Compression in Plate	1.04
15	GYCF	Girder Yield Compression in Flange	1.224
16	GYCP	Girder Yield Compression in Plate	1.224
17	GYTF	Girder Yield Tension in Flange	1.224
18	GYTP	Girder Yield in Tension in Plate	1.224
19-21	FCPH	Frame Collapse, Plastic Hinge	1.60
22-24	FYCF	Frame Yield, Compression in Flange	1.224
25-27	FYTF	Frame Yield, Tension in Flange	1.224
28-30	FYCP	Frame Yield, Compression in Plate	1.224
31-33	FYTP	Frame Yield, Tension in Plate	1.224

3.2. Analysis module

A total number of five loading conditions were defined according to BV requirements [9, 10] along with the appropriate seventeen load cases. Pressure distribution (internal and external, static and dynamic) for all load cases were supplied by ANAST via VERISTAR file [11]. All conclusions were based on these load cases. In addition, representative design sloshing pressure acting on plating and stiffeners of tank inner shell was calculated using BV sloshing module. Figure 3 shows sloshing pressure in kN/m^2 calculated for the defined tank geometry. According to defined sloshing pressures, additional set of minimum values was defined in order to satisfy the necessary local strength due to sloshing. This additional set was implemented regarding the inner shell of tank structure (plating and stiffeners).

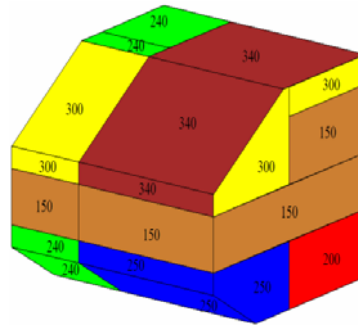


Fig. 3 Sloshing pressure (in kN/m²) acting on plating and stiffeners of tank inner shell

Slika 3. Tlak zapljuskivanja (u kN/m²) definiran za oplatu i uzdužnjake unutarnje strukture tanka

3.3. Synthesis module

Problem can be fully decomposed regarding local variables and attributes but coupling is present in calculation of design criteria. Each of them is dependent on stress fields obtained from FEM analysis and therefore dependent on structural stiffness and load vector.

Table 3. Variable schedule in the design procedure (\bar{x} = fixed, n = number of cycles)

Tablica 3. Redoslijed varijabli u projektnom postupku (\bar{x} = nepromjenjiva varijabla, n = broj ciklusa)

	Variables: Optimization subproblem P^{ij}	LOCAL VARIABLES SETS i				GLOBAL VARIABLES SET j	
		i	subset x^1	subset x^2	subset x^3	subset x^4	j $x^{Ship j}$
Scantlings opt. $i=1-4$, $j=1$	P^{11} – Long. tank structure	1	$x^{1,n}$	$\bar{x}^{2,n}$	$\bar{x}^{3,0}$	$\bar{x}^{4,0}$	1 $x^{Ship 1} = \{\bar{s}_{w1}, \overline{bbs}_1, \overline{mat}_1\}$
	P^{21} – Transverse structure in tank	2	$\bar{x}^{1,n-1}$	$x^{2,n}$	$\bar{x}^{3,0}$	$\bar{x}^{4,0}$	1 $x^{Ship 1} = \{\bar{s}_{w1}, \overline{bbs}_1, \overline{mat}_1\}$
	P^{31} – Cofferdam strakes	3	$\bar{x}^{1,n}$	$\bar{x}^{2,n}$	$x^{3,0}$	$x^{4,n}$	1 $x^{Ship 1} = \{\bar{s}_{w1}, \overline{bbs}_1, \overline{mat}_1\}$
	P^{41} – Cofferdam plates	4	$\bar{x}^{1,n}$	$\bar{x}^{2,n}$	$x^{3,0}$	$x^{4,n}$	1 $x^{Ship 1} = \{\bar{s}_{w1}, \overline{bbs}_1, \overline{mat}_1\}$
Sensit. a. $i=5$, $j=2-4$	P^{52} – stiffener spacing	5	x^{1Opt}	x^{2Opt}	\bar{x}^{3Opt}	\bar{x}^{4Opt}	3 $x^{Ship 3} = \{\bar{s}_{w2}, \overline{bbs}_2, \overline{mat}_1\}$
	P^{53} – material	5	x^{1Opt}	x^{2Opt}	\bar{x}^{3Opt}	\bar{x}^{4Opt}	4 $x^{Ship 4} = \{\bar{s}_{w2}, \overline{bbs}_1, \overline{mat}_2\}$
	P^{54} – web spacing	5	x^{1Opt}	x^{2Opt}	\bar{x}^{3Opt}	\bar{x}^{4Opt}	2 $x^{Ship 2} = \{\bar{s}_{w2}, \overline{bbs}_2, \overline{mat}_1\}$

Where: $P^j = \{P^{Local var. i, global var. set j}\}$ ship cycle or variant

To decrease the size of the problem in the first design cycles, the ‘weak’ coupling between longitudinal tank structure and cofferdam is recognized and used to decouple problem on separate optimization of tank and cofferdam structure. Convergence of the process is obtained via unified response analysis of all modules. Accordingly, the design procedure was performed in the following steps:

1. Initial optimization of longitudinal and transverse tank structure (problem P^{11+21}).
2. Optimization of cofferdam structure (problems P^{31+41}), decoupled from the tank optimization sub-problem. (Optimization problem were solved using SLP algorithm inbuilt in MAESTRO software).
3. Joint optimization and analysis of problems $P^{11+21+31+41}$.
4. Sensitivity analysis of the optimal solution using problems P^{52} , P^{53} and P^{54} , where $i = 5$ is optimal solution of scantling optimization. Optimal design $O^{1Concept}$ was generated.
5. Based on sensitivity analysis final optimization of preferred variants from step 5 was performed and optimal solution was generated, $O^{3Preliminary}$.

6. The standardization based redesign is performed including sub optimization with respect to the remaining free variables. Final design with all satisfied constraints is denoted as \mathbf{D}^4 .

4. Structural optimization results

History of defined design attributes (structural mass, VCG and safety) for optimization sub-problems \mathbf{P}^{11} , \mathbf{P}^{21} , \mathbf{P}^{31} and \mathbf{P}^{41} (Table 3) is given in Fig. 4 with respect to optimization cycle. To get better in view into the contribution of particular structure to total mass, results are given separately for middle tank and cofferdam structure.

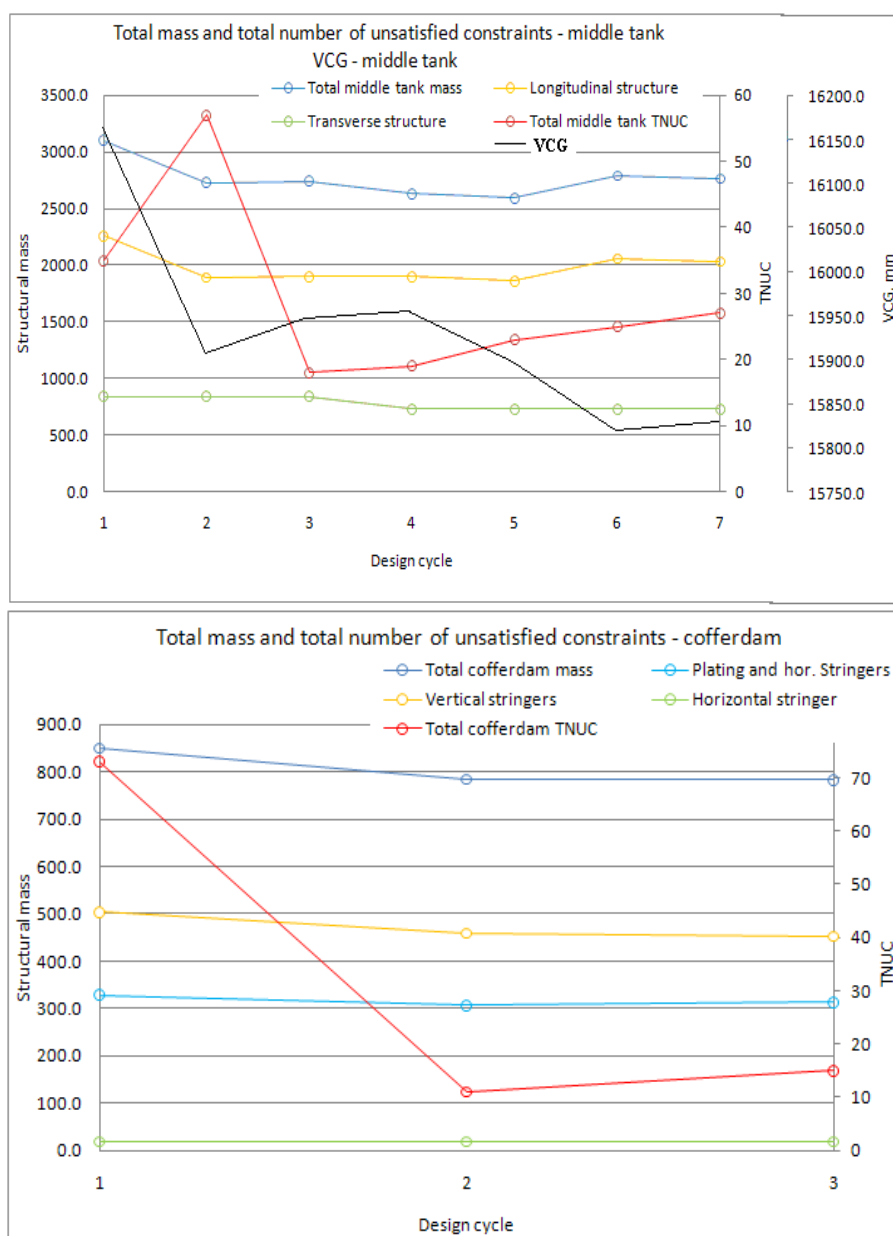


Fig.4 History of structural mass and number of unsatisfied constraints (TNUC) for middle tank and cofferdam

Slika 4 Promjena mase i ukupnog broja nezadovoljenih ograničenja (TNUC) za strukturu tanka i koferdama

Optimization of middle tank structure has shown strong coupling between longitudinal and transverse structural elements. Design cycle 1 at Fig. 4 shows initial structural mass of longitudinal (orange color) and transverse (green color) elements. During first three cycles

mass of transverse elements is constant, while mass of longitudinal elements is decreasing. At 4th cycle mass of transverse structure was decreased due to new scantlings and was kept constant during the rest of design cycles, but due to that the mass of longitudinal structure is increasing. It can be concluded that no improvement can be achieved by modifying transverse structure.

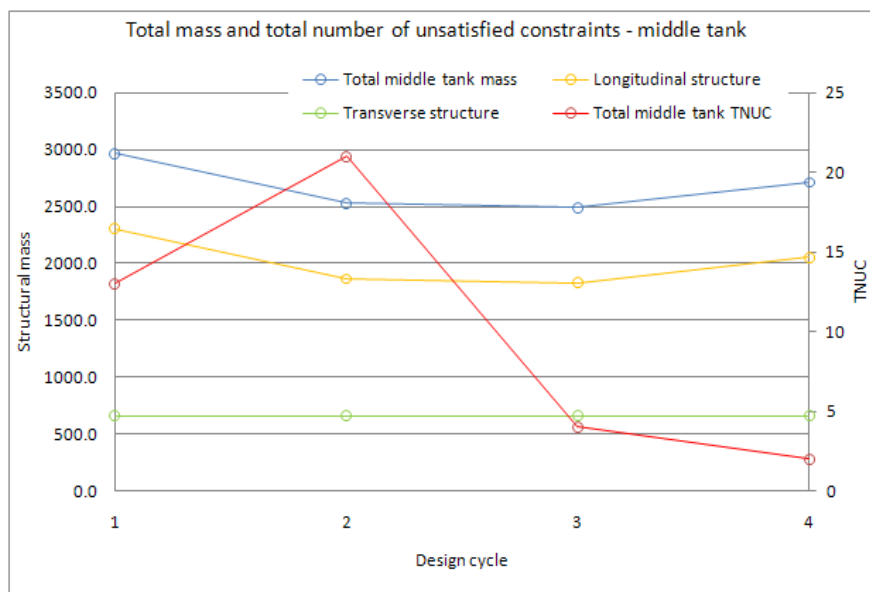
As given in the design sequence flowchart (Fig. 1), sensitivity studies are done when optimization procedure converged to the optimal solution. Three sensitivity studies related to tank structure were done regarding:

- breadth between stiffeners,
- material selection,
- web frame spacing.

Sensitivity analysis regarding number of stiffeners has shown that additional savings regarding structural mass can be achieved by providing additional stiffener. Cost of a similar structure is higher (greater length of welding) and can be evaluated if the cost parameters are given. Also, sensitivity analysis regarding material type has shown that additional savings regarding structural mass can be achieved by providing higher tension steel for stiffener material. Cost of such structure is higher (cost of material), but no significant gain has been identified in structural weight to justify that solution. Finally, sensitivity analysis regarding web frame spacing has shown that by reducing the web frame spacing additional savings can be achieved with respect to structural mass and also with respect to cost of welding. Following that reasoning, a structure with maximum possible web frame spacing is chosen for the next step of optimization procedure.

Due to new web frame and stiffener spacing new sloshing minimum were calculated. Remodeled LNG ship structure was optimized using MAESTRO software. Mathematical model of optimization problem was formulated according to described design procedure, using the defined set of the design variables, constraints and attributes. When defined, problem was solved using sequential linear programming method (SLP).

History of design attributes (structural mass, cost, VCG and safety) is given in Fig. 5 with respect to optimization cycle. To get better view into the contribution of particular structure to total mass, results are given separately for middle tank and cofferdam structure. Three optimization cycles were performed, as shown in the Fig.5. Additional design cycle (4th) is added and it represents standardization of achieved optimum scantlings.



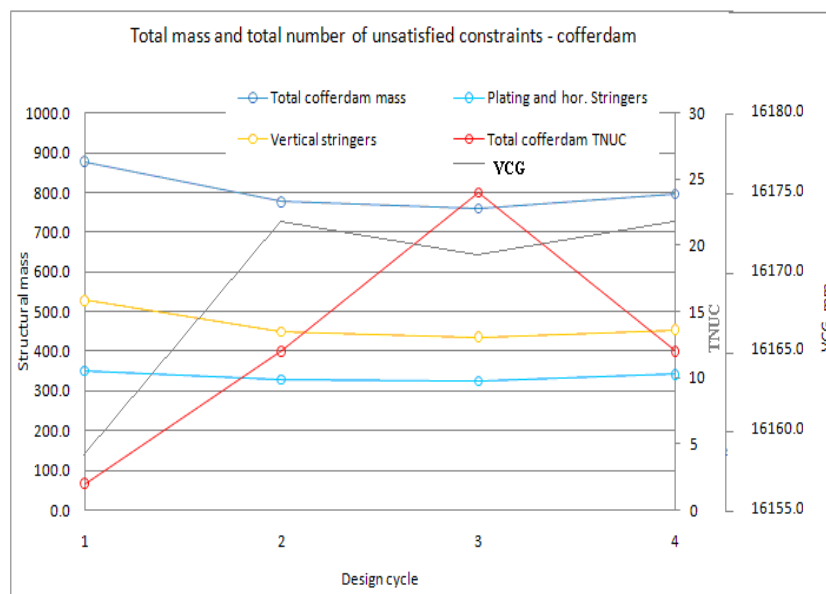


Fig. 5 History of structural mass and number of unsatisfied constraints (TNUC) for middle tank and cofferdam

Slika 5. Promjena mase i ukupnog broja nezadovoljenih ograničenja (TNUC) za strukturu tanka i koferdama

Summary of preliminary optimization results are given in Table 4. After the optimization procedure, the standardization of optimal structure achieved in preliminary design phase was performed in order to obtain technologically feasible design of LNG structure. All obtained scantlings were rounded off to some reasonable values.

Table 4. Summary of preliminary optimization results

Tablica 4. Sažetak rezultata preliminarne optimizacije

Design solution	Structural mass, (t) (middle tank)	Mass savings, %	Safety (TNUC)	VCG, (mm)
Initial, P^0	3931	/	110	16155
Optimal, $O^{3\text{Preliminary}}$	3251	17.3	3	15931
Standardized, D^4	3507	10.8	0	15951

When standardized, structural model of LNG ship was further analyzed using MAESTRO in order to inspect the properties of the new proposed solution. Results of stress and adequacy analysis for the final solution as an example are shown in Figs. 6 and 7.

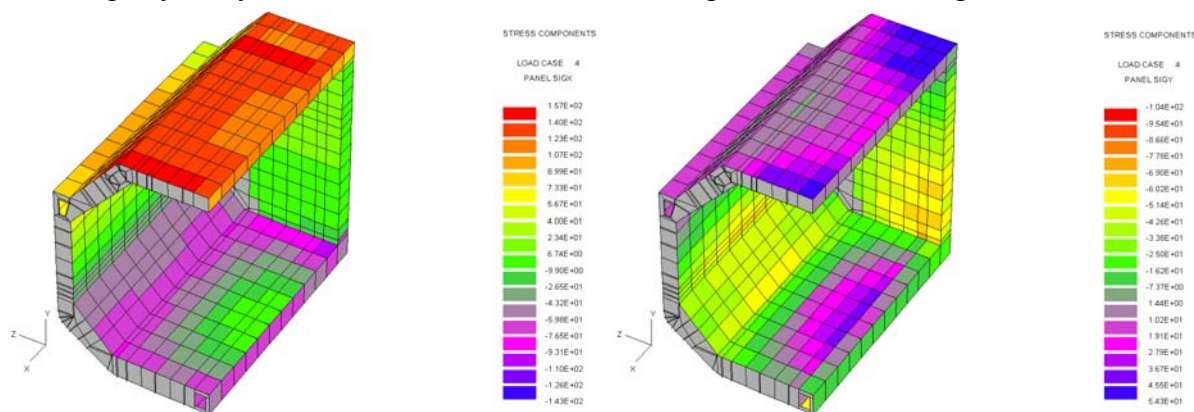


Fig. 6 Results of final analysis – σ_x and σ_y component stresses

Slika 6. Rezultati finalne analize– σ_x i σ_y komponentna naprežanja

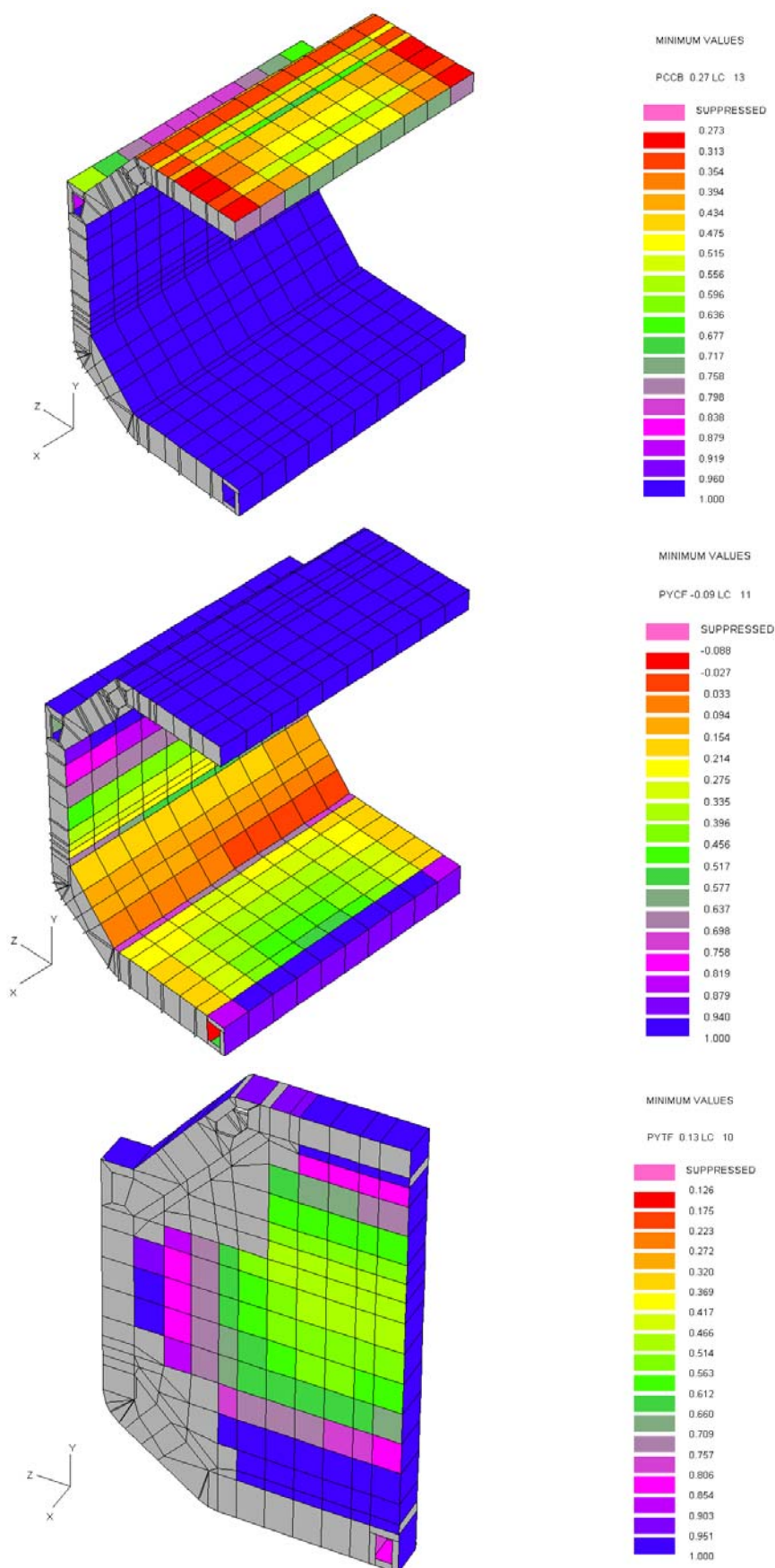


Fig. 7 Results of final adequacy analysis (tank and cofferdam)-structural feasibility criteria PCCB and PYTF

Slika 7. Rezultati finalne analize podobnosti (tank i koferdam)– strukturni kriteriji PCCB i PYTF

5. Conclusion

Optimization of a real ship can offer a significant help to the ship designer because it can optimally redistribute material, reducing weight of initial model and increasing its safety. Also, as presented in this report, it can help in decision making regarding various topological and geometrical variables.

According to assignment the optimization of tank and cofferdam structure was performed in order to determine the optimal solution with respect to objective function (minimization of total mass and cost) and safety criteria.

CONCEPT DESIGN PHASE:

First step of the concept design procedure was initial exploration of the design space which was done for the initial model P^0 within six design cycles. Structural mass and VCG were successfully decreased and safety was increased (Table 5) and solution $O^{3\text{Concept}}$ was generated.

Second step of the concept design procedure was sensitivity analysis in order to inspect the sensitivity of breadth between stiffeners, material type and web frame spacing on the defined design objectives. Sensitivity analysis has shown that by increasing web frame spacing and decreasing breadth between stiffeners is possible to gain additional savings.

Table 5. Summary of all achieved results

Tablica 5. Sažetak postignutih rezultata

	Design solution	Structural mass (middle tank)	Mass savings, %	Safety (TNUC)	VCG, mm	Normalized cost
Concept desing	Initial, P^0	3931	/	110	16155	1.00
	Optimal, $O^{1\text{Concept}}$	3457	12.0	42	15957	0.87
Preliminary design	Optimal, $O^{3\text{Preliminary}}$	3251	17.3	3	15931	0.85
	Standardized, D^4	3507	10.8	0	15951	0.95

PRELIMINARY DESIGN PHASE:

Based on concept design phase conclusions, the third step of the overall design procedure was performed i.e. the standard preliminary design phase optimization. It resulted with the optimal design $O^{3\text{Preliminary}}$ where savings are up to 17%. Complete re-analysis was performed in order to determine strength and safety level of the final standardized design D^4 of LNG ship, obtained from the optimal design $O^{3\text{Preliminary}}$. The results of the adequacy analysis were considered satisfactory for the preliminary design phase with respect to BV requirements. Subsequent detail design phase should concentrate on several higher stress areas identified in this phase.

A comparison between the results reveals that the proposed standardized design D^4 is acceptable from economical point of view, because of 10.8% of savings in structural mass and at least 5% of savings in the cost of structure.

Total reduction of 17% in design weight for optimal design is rather high, but it also depends on the starting design (since it is the total saving of concept and preliminary design phases). Savings of 12% obtained during concept design phase is also rather high, but it is often achieved with greater changes in prototype parameters (e.g. web frame spacing). Savings of 4 – 7 % in weight during the preliminary design phase is standard with respect to the good concept design, as achieved in this example.

Optimal point of the preliminary design phase is a good starting point for standardization, usually compared to the initial Yard design. As demonstrated in the example, standardization has brought savings down to 10.8%, but Yard designers can do it better. Knowledge of the optimal (non-standardized) design scantlings (and savings in weight) is offering the designer an excellent opportunity to perform the refined standardization procedure regarding material quantities and production considerations of particular Yard.

A comparison between the results reveals that proposed design (standardized scantlings) is offering simultaneously savings in structural mass and cost, increase in safety (due to logical material distribution) and therefore maturity and the potential of the applied approach to design.

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